

FLAME SPREAD ACROSS LIQUIDS

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Introduction

The principal goal of our recent research on flame spread across liquid pools is the detailed identification of the mechanisms that control the rate and nature of flame spread when the liquid pool is initially at an isothermal bulk temperature that is below the fuel's flash point temperature. In our project, we specialize the subject to highlight the roles of buoyancy-related processes regarding the mechanisms of flame spread, an area of research cited recently by Linan and Williams [1] as one that needs further attention and which microgravity (μg) experiments could help to resolve. Toward resolving the effects of buoyancy on this flame spread problem, comparisons – between 1g and μg experimental observations, and between model predictions and experimental data at each of these gravitational levels – are extensively utilized. The following describes the present experimental and computational foundation supporting identification of the mechanisms that control flame spread in the pulsating flame spread regime for which long-duration, μg flame spread experiments have been conducted aboard a sounding rocket. See [2] for further details of the experimental hardware.

Results

Normal Gravity Experiments

A series of 1g experiments was recently performed examining low-speed, forced air flow effects on pulsating flame spread [3]. These experiments used top and side-viewing flame imaging systems, liquid-phase Rainbow Schlieren Deflectometry (RSD), two liquid-phase Particle Image Velocimetry (PIV) systems, and Infrared (IR) thermography for surface temperature determination. A 30 cm long x 2 cm wide x 2.5 cm deep fuel tray was located inside a 10 cm x 10 cm cross-sectional area flow duct to provide a laminar, forced-air flow, ranging from 5 cm/s to 30 cm/s in the freestream over the fuel tray. The values of opposed, forced-air flow velocity were selected to be on the same order or less than that which occurs due to buoyancy in 1g experiments of this scale [4]. The experiments were conducted with dry air at 1 atm and the temperature of the butanol fuel was between 20 and 21 C (depending on the test) at the time of ignition; the dry air was utilized to avoid potential complications from water absorption in the fuel prior to the test.

The 1g flame shape near the leading edge is unaffected by the very low, opposed, forced air speeds (<10 cm/s), as it is overwhelmed by the effects of naturally induced buoyant air flow. As the forced air speed is increased, the trailing portion of the flame is pinned closer to the surface; the trailing plume that develops is filled with soot and the plume itself is sporadically blown downstream horizontally, in the opposite direction to the spreading flame, by the forced air flow. The 1g pulsating flame frequency is affected by the forced opposed air flow. Figure 1 shows the pulsation frequency increases as the forced, opposed air flow decreases from 30 cm/s to 5 cm/s.

The thermal gradients in the RSD image indicate that the depth to which the liquid is heated is not affected systematically by the air speed. The near-surface behavior cannot be analyzed because the RSD images were all off-scale in this region. The PIV systems showed vortical motion consistent with the RSD, but showed motion a couple cm ahead of the flame, that was not apparent in the RSD since the flow is not heated sufficiently at that point. Detailed tests of the quiescent case are currently being performed.

In all of the 1g opposed air flow tests, the IR images show that a pair of thermal vortices form on the pool surface 1-2 cm ahead of the flame during the crawling phase of the flame pulsation cycle [5]– see Fig. 2. These indicate sideflow processes which are not apparent from the top view of the flame shape or from the side-view PIV. The IR images also verify the existence of a surface temperature valley [6] if one scans axially along a line at constant distance from the edge of the fuel tray. These are further confirmed by thermocouple measurements along the surface, as shown in fig. 5.

Given the predicted importance of the gas-phase recirculation cell to flame pulsation mechanism [7], it is surprising how little experimental measurement has been done to verify its existence. Initial LDV and PIV experiments were not able to resolve the detailed, near-surface phenomena [4, 8]. Smoke-wire visualization of a recirculation cell was successful in the very slow flame spread across fuel-soaked beds and even across solids [9]; it is not clear that this is the same phenomena as predicted for flame spread across pure liquid fuels. Smoke-wire visualization was applied recently, to this problem and verified, for the first time, more of the details of the recirculation cell, as shown in fig. 3. Quoting from [10]: “The flame is spreading from right to left (against the freestream air), while the smoke is moving off the wire initially from left to right because of the forced air flow. As the smoke and flame close on each other, the smoke front begins to curl downward because, as predicted, the surface flow just ahead of the flame is moving from right to left, and the no-slip condition is fulfilled. The smoke front then begins to move upward and defines the extent of the cell. At the time of the smoke release, the flame was nearing the end of the crawl (slow) phase of the cycle when it entered the Field Of View. According to the numerical model, this is the moment when the recirculation cell should be largest, and in fact that is what we saw from this test and many others. However, when the flame entered the FOV during or right after the jump phase of the pulsation cycle, we saw no cell, or a very poorly formed one, which again agrees with the model since it predicts the cell is destroyed during a jump.”

Using the apparatus described above, we also performed some 1g tests with concurrent air flow. Few experiments – either in 1g or μ g – with concurrent air flow have been conducted in the pulsating regime, and those have focused primarily on the effects of wind velocities, typically above 1 m/s, on the flame shape and average flame spread rate [11, 12].

As can be seen in figure 8, the flame front is much higher than in the opposed flow case (see [2] for a comparison figure) and even takes on a “C” shape for the highest flow rates. This near-vertical front is due to the forced flow offsetting the induced buoyant flow. The flame position vs. time is shown in fig. 1 for four values of the concurrent flow rate. At very low concurrent air speeds, the pulsation frequency continues to increase (relative to the opposed air flow results) in accordance with increases in the concurrent air speed. The fact that the flame characteristic is still one of pulsation indicates that, despite the concurrent air flow, buoyancy remained the most influential force in the gas-phase flow field (consistent with the flame shape results); its dominance however is progressively reduced as the magnitude of the forced, concurrent air flow increases. At the highest concurrent air speeds (20 - 30 cm/s), the forced air flow dominates over buoyancy, and the flame loses its pulsating spread behavior; instead it gradually, and then rapidly, accelerates across the surface of the pool.

Unlike the opposed flow tests, a liquid-phase thermal vortex with a well-defined center under the flame is seen only at the lowest concurrent air flow speeds. Over most of the range of concurrent air flow speeds, the liquid phase is, instead, without a well-formed thermal vortex. There is movement of the thermal gradients in the liquid phase which accompanies the flame but this movement is erratic in direction and without a well-defined vortex center.

At the lowest speeds in the concurrent air flow tests, the IR images do not show twin thermal vortices but indicate a long preheat length (a maximum of about 3 - 4 cm) with asymmetric curls much closer to the flame during the crawling phase of pulsating spread. The front of the preheat region farthest from the flame is parabolic and symmetric. As the speed of the concurrent air flow increased, there is an absence of the asymmetric curls, the preheat distance increases to several centimeters, and the shape at the front of the preheat zone remains parabolic and symmetric (see Fig. 2).

Microgravity Experiments:

Our earlier work showed that flames do not spread across shallow, alcohol pools in air at 1 atm in microgravity unless a forced air flow is provided in a direction opposing the flame [13]. These early experiments lacked detailed diagnostics and did not elucidate the effects of pool depth where buoyancy might be important. Low-speed air flow, at levels comparable to and below those associated with buoyantly induced air flow, were shown to have a major effect on flammability and flame spread across solid fuels in μ g. This motivated an examination of the effects of air flow speed and direction for the case of liquid pools.

At the previous workshop we reported on the results of the first of a set of three μ g experiments – with forced opposed air speeds of 5 to 30 cm/s -- in the same heavily instrumented apparatus described above and in [2] – that were conducted in a sounding rocket, rather than a drop tower, because of the μ g test time required to fill the tray with fuel, to reach quiescence in the liquid, and for the flame to spread, and finally because of the volume required by the diagnostic instrumentation. The results of the full set are now presented.

In every case, the μ g flame appears entirely blue and therefore soot-free (in contrast to the soot-filled flames in 1g). This occurs despite a forced air speed up to 30 cm/s - the same order as naturally induced by buoyancy. A reason for this difference is offered below. The intensity of the μ g flame, especially far from the leading edge, is also less than comparable blue portions of the 1g flame. These findings are consistent with lower flame temperatures in μ g. In μ g, only one large thermal vortical structure appears in the liquid phase, as imaged by RSD, moving steadily with the flame in a manner again analogous to the crawling phase in the 1g pulsation cycle. The RSD also shows heating extends deeper into the fuel depth, and both the IR and RSD show surface preheating farther ahead of the flame in μ g.

The experimental results regarding spread and extinction are as follows (fig. 4):

- at 30 cm/s opposed air flow, the flame spreads slowly and near-steadily.
- at 20 cm/s, the same occurs but the flame spreads much more slowly.
- at 10 cm/s, the flame initially spreads slowly, weakens as it spreads, and then flashes in a near-extinction behavior.
- at 5 cm/s, the flame begins to spread, then flashes partially across the pool and extinguishes. (This last test was actually a second burn of the same fuel following the 20 cm/s burn.)

As the forced air flow speed is reduced, the spread rate diminishes and the thermal effects ahead of and beneath the flame are felt farther from the flame front. With further reductions in the forced air speed, the flame weakens to the point that flame spread cannot be sustained. This is consistent with the drop tower observations in both axisymmetric and rectangular trays of smaller dimension for quiescent spread. In distinct contrast, the flame is always sustained in 1g at these forced air speeds and indeed with no forced air flow.

The μg flames also showed a different liquid surface temperature structure comprised of larger, asymmetrical curls ahead of the flame [2]. Nonetheless, the μg test results provide further confirmation of the surface temperature valley and for the need for high spatial and temporal resolution in experiments. As shown in fig. 5, when the leading edge of the visible, μg flame is only 2 mm in front of the thermocouple junction, the surface temperature is 36.2 C (very near the flash point of butanol). When the leading edge of the μg flame is 2 mm past this junction, the temperature is 51.7 C, and continues a sharp rise until the main body of the trailing flame is sufficiently far off the surface to cause the surface temperature to dip briefly. Then as the trailing flame establishes over the surface, the pool surface temperature again rises toward the fuel's boiling point.

In μg , because the flame spread is slow (cf. fig. 4), liquid motion is observed by the PIV systems much farther ahead of the flame than in 1g, and the velocity under the flame leading edge is faster, being at least 10 mm/s in the 30 cm/s test [5]. It is certainly higher than 10 mm/s, because very near the leading edge, the motion was so fast the particles streaked and were difficult to track. The center of the vortex preceding the flame is deeper in μg , but the overall pattern looks relatively similar [5].

The slow μg flame velocity, observed at all forced air speeds, is an order of magnitude less than that which occurs on Earth in the uniform spread regime [11]. This behavior, supported by the RSD and PIV measurements, suggests the flame spread character is unrelated to classically defined uniform spread. Instead, it is similar in magnitude and character to the slow spread velocity associated with the crawling phase of the pulsation cycle or the pseudo-uniform spread regime.

Definitive tests with concurrent air flow in microgravity have yet to take place. Using a 15 cm long x 2 cm wide x 1 cm deep tray inside a 4 cm square cross section flow duct we have performed a few preliminary tests in the 5.2 sec. Zero-Gravity Facility at NASA Lewis. The concurrent air flow rates tested were 20 cm/s and 30 cm/s with 1-butanol as the fuel at temperatures ranging from 21 to 24 °C. The flame spread readily at in the 30 cm/s cases, with a distinctively different shape than the opposed flow cases. Instead of being flat across the front, it was steeply parabolic as seen from above. From the side, it had a stand-off distance of several mm, in contrast to the near zero stand-off distance in opposed flow. There were no flame pulsations, and the spread rate was higher than the opposed case. In contrast, at 20 cm/s the flame ignited, spread a couple of cm, and then extinguished. In only one case did we witness flame spread at 20 cm/s, and that was at the highest temperature of 24.3 °C in which case it appeared similar to the 30 cm/s case.

Comparison With Models:

The numerical model of [7] predicts that the mean flame spread rate and pulsation frequency increase with opposed air velocity in 1g. This is because the pulsation frequency is predicted to be inversely proportional to the maximum length of the gas-phase recirculation cell (the longer the cell, the more time is required to accumulate a flammable mixture). The opposed flow is predicted to reduce the length of this cell. Unfortunately, this trend appears to be different from the experimental observations for unknown reasons. The model also predicts that the mechanism causing pulsating flame spread is independent of gravity as long as a sufficient, opposed air flow in the freestream occurs (in 1g this is induced by buoyancy, in μg this is provided by the mechanical fan). Thus, the model predicts that pulsating spread can and will occur in μg ; however, as noted above, the μg experiments to date show a slow, near-steady spread.

To try to explain this disagreement, dimensional effects were examined [5]. The model is two-dimensional and cannot account for the effects of a finite flame width or the sidewall losses associated with the tray. One consequence of this difference is that hot gas expansion in the model is inherently constrained to the vertical and longitudinal directions. In general, however, hot gas expansion can occur in these directions and in the transverse direction. Hence gas expansion toward the sides – a mechanism available in the experiments but not in the model – could decrease the extent of hot gas expansion ahead of the flame.

This effect has not yet been verified in μg experiments, but successful laser sheet smoke-flow visualization of the lateral hot gas expansion was recently achieved for the first time in 1g experiments [10]. As can be seen in this top view (fig. 6), all but the central streakline are laterally displaced as the flame approaches providing the first clear evidence of lateral hot gas thermal

expansion. The central streakline is not laterally displaced, but instead forms the gas-phase recirculation cell shown in figure 3. The other streaklines show that the oncoming air flow is perturbed at least 2 cm ahead of the flame front, and the lateral expansion at the front location is of the order of 5 mm. The maximum streakline displacement occurs where the flame meets the side wall, which is a few mm behind the near-flat flame front due to curvature. After passing the flame front, the flow begins to turn back toward the flame again as it is caught in the buoyantly-driven flow; at some point it is no longer visible, probably because it is carried upward and out of the light sheet. The flow toward the trailing flame serves to raise the reaction rate and elevate the flame temperature to the point that soot is formed. The absence of this side flow phenomenon likely suppresses soot formation in the μg experiments described above, resulting in the all-blue, μg flames even at the relatively high forced air speeds. Because there is no lateral air inflow driven by buoyancy that would tend to cancel the lateral expansion, the effects of hot gas expansion might be more appreciable in these μg experiments (and other μg flame spread studies presently underway). To try to estimate the importance of this mechanism, the model was run with the hot gas expansion artificially set to zero [5]. Figure 7 shows excellent agreement is found between the model and experiment in terms of spread rate and the spread character.

Modeling of concurrent flow effects on flame spread in 1g is in its early stages and is presently restricted to shallow pools of n-propanol [14]. As the concurrent air speed increases from zero, the pulsations become more frequent. This is consistent with the experimental observations. When the air speed reaches 30 cm/s, the predicted spread becomes very erratic, failing to progress on a time-averaged basis very far forward. Instead it appears to oscillate irregularly forward and backward with large amplitude. This is in contrast to the experimental results obtained to date; again the differences in the dimensionality between model and experiment may contribute to the disagreement.

The model's predictions for flame spread behavior with concurrent flow in μg are much better behaved. For these same initial temperatures at μg , the model predicts that, at speeds less than 20 cm/s: (a) consistent with predictions for quiescent air, extinction occurs if only a small amount of vaporization occurs prior to ignition; and (b) flame spread is uniform when the fuel vapor distribution is fully developed prior to ignition.

As discussed above, preliminary tests in the 5.2 sec Zero-Gravity Facility confirm point (b) where uniform spread was found; the limited test time, however, did not enable spread across the entire fuel tray. Longer duration experimental examination for these flow conditions is planned in both narrow and wide trays [5]; the latter should mitigate the effects of lateral transport and hot gas expansion. Pulsating spread is not predicted in μg with forced, concurrent air flow because no opposed gas-phase flow exists to form the gas-phase recirculation cell ahead of the flame. This generic characteristic is quite consistent between experiment and model, regardless of gravitational level: pulsating spread occurs only when there is a gas-phase recirculation cell. A recirculation cell exists when there is: (1) surface convection moving with the flame at speeds higher than the flame spread rate and (2) gas-phase convection in the freestream air moving opposite to the flame spread direction.

Conclusions

The above description provides many of the detailed findings from recent experiments and modeling of flame spread across liquid fuel pools. This area of research is gaining renewed interest by groups around the world. Among the more important observations so far, of all of our research to date, are the following, drawn from [15]:

Pulsating spread is affected both by liquid-phase transport (as seen by the requirement for liquid-phase convection preceding the flame and by the pulsation dependence on tray depth) and by gas-phase transport (as seen by the effects of oxygen concentration, diluent type, air-flow direction and speed). A key insight is suggested by the model: the existence of pulsating spread correlates with the existence of a gas-phase recirculation cell. Smoke flow visualization in 1g, forced-flow, pulsating spread experiments has now verified the predicted development and destruction of this gas-phase recirculation cell.

Even with forced, opposed air velocities of the same order of magnitude as that induced naturally by buoyancy in normal gravity, the μg flame behavior is completely different. The preheat length, the depth of the thermal vortex, the surface flow (distance, character, and magnitude) ahead of the flame, the rate of fluid rotation in the vortex, the flammability, the flame intensity, soot formation (none in μg), and the flame spread rate and character are all affected by the magnitude of forced air flow in μg .

Pulsating spread under forced opposed-air flow conditions in μg is predicted, however it remains unobserved experimentally. The difference is presently attributed to the effects of lateral hot gas expansion that can not be directly included in the model nor completely eliminated from the experiments. Recent experiments verify that hot gas expansion affects the approaching flow up to 2 cm ahead of the flame and causes a displacement of streaklines in normal gravity; the effect is speculated to be greater in μg .

Low-speed concurrent air flow, at a magnitude similar to that induced by buoyancy in the opposite direction, affects the existence and nature of pulsating spread in 1g. As the concurrent air speed increases to a magnitude of 30 cm/s, pulsating spread disappears. The model and experiments presently disagree, for unknown reasons, on the flame spread character at this air speed.

The recent application of detailed diagnostics to the problem of flame spread across liquid pools exposed inherent three dimensional effects. Measurement of the liquid surface temperature with an infrared camera revealed twin vortices in 1g, and large, asymmetric swirls in μg [5], and smoke flow visualization in 1g shows strong lateral displacement of the incoming stream [10]. This indicates a need to extend the existing numerical model to three dimensions.

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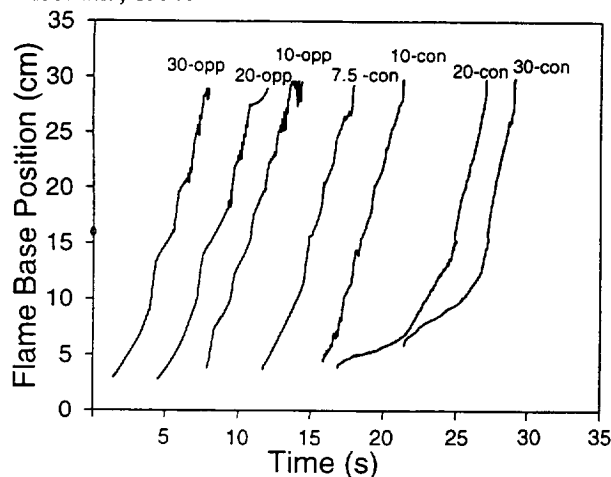


Figure 1. Flame position vs. time for several forced air flow velocities, both opposed and concurrent.

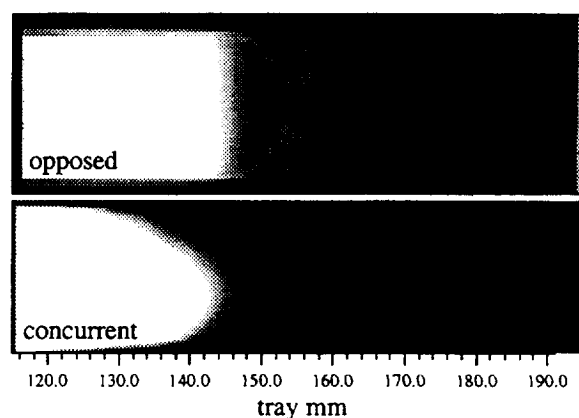


Figure 2. Infrared top view of the liquid surface temperature ahead of a spreading flame for two air flow directions at 30 cm/s

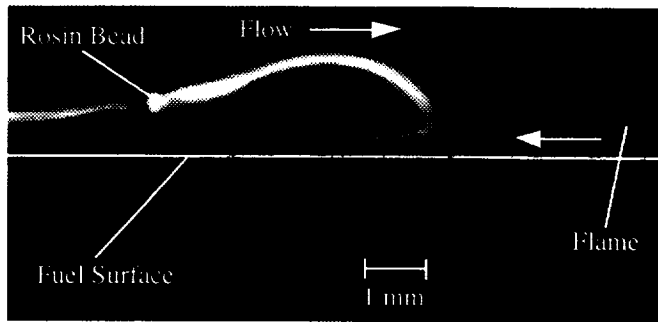


Figure 3. Smoke flow visualization of the recirculation cell in front of a pulsating flame. 30 cm/s opposed flow.

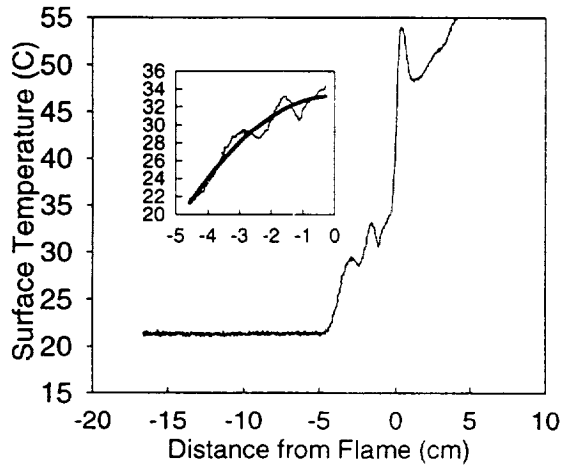


Figure 5. Liquid surface temperature ahead of a spreading flame in microgravity for an opposed flow rate of 30 cm/s. Inset shows square root fit.

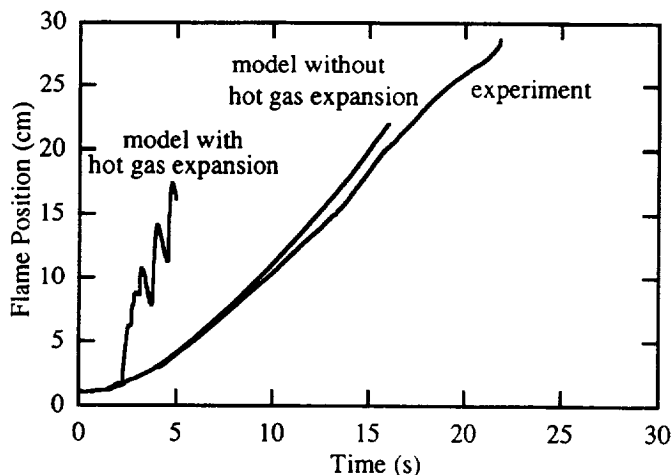


Figure 7. Flame position vs. time with a 30 cm/s opposed flow in microgravity showing effect of eliminating hot gas expansion from model.

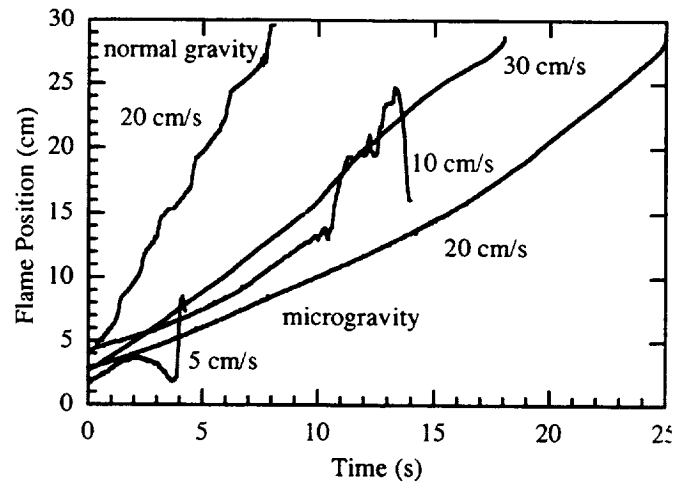


Figure 4. Flame position vs. time for four opposed air flow rates in microgravity, and one typical normal gravity case.

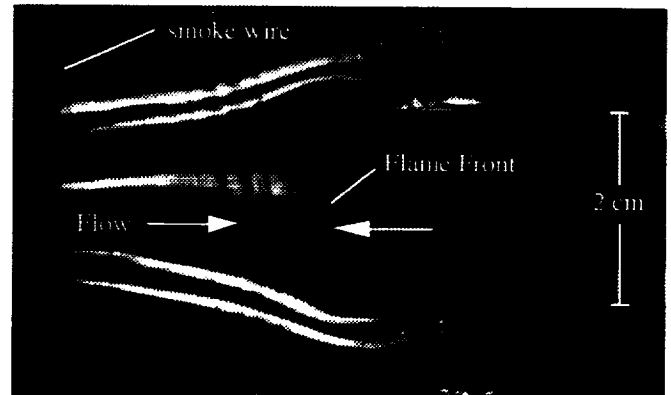


Figure 6. Top view of flame spread showing divergence of smoke streaklines due to hot gas expansion at the flame front. Opposed flow of 30 cm/s..

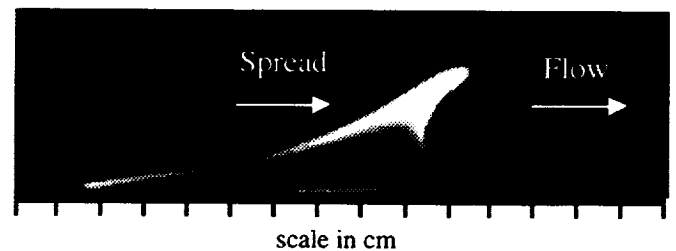


Figure 8. Side view flame shape with a 30 cm/s concurrent flow in normal gravity. Refer to [2] for opposed flow shapes in both normal and microgravity. Next round of sounding rocket flights will measure flame spread in concurrent flow